F-111 Store Trajectory Analysis

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ABSTRACT

The analysis of store separation by computational fluid dynamics (CFD) techniques holds great promise for reducing aircraft-store certification testing. The primary concern with CFD application is the question of accuracy. This question of how much confidence should be placed on CFD generated loads data and trajectories is addressed using an uncertainty analysis technique. The process requires a formalized approach to evaluating the uncertainty associated with the CFD produced loads data. This is accomplished by the use of belief function calculus to combine uncertainty estimates of fundamental metrics (grid resolution, solver complexity, accuracy of surface definitions…) into a composite uncertainty estimate for the force and moment data. This process provides the "error bars" associated with the CFD loads data. The store loads data is used in a six degree-of-freedom code to produce the nominal trajectory. The uncertainties are tracked through the process in order to provide a confidence estimate that the store will remain within a given value (e.g. 5%) of the nominal trajectory. The uncertainty analysis technique is applied to CFD force and moment data generated for the release of a Small Smart Bomb (SSB) from the forward carriage location of the F-111 aircraft at flight Mach numbers of 0.8 and 0.95.

1.0 INTRODUCTION

An increasing number of methods are being used to assess the safe separation of a store from an air vehicle, including captive-trajectory testing, dynamical analysis using grid data, incremental flight tests, and computational fluid dynamics. Because of the cost typically associated with performing this type of analysis using flight tests, there is an increasing desire to certify more stores by analysis. To accomplish this, there must be improved understanding of the relative strengths and weaknesses of CFD, sub-scale testing, and integration of force measurements to obtain trajectories, as well as having a method to appropriately combine these different analysis methods into a coherent characterization of the separation environment. This analysis is further complicated by the minimal amounts of available data that occasionally disagree and can have a number of different sources for the error. Not only must the error in the force and moment measurements/predictions be determined, but also the impact that these errors have on the store's trajectory must be ascertained. Furthermore, a capability to assess the different predictions and determine which parameters are driving the uncertainty in the trajectory prediction is strongly desired. This paper addresses an approach for this type of analysis using the separation of a 250-pound class weapon from the F-111 aircraft weapon bay as an example.

This series of test are of particular interest because both traditional CFD[1] and wind tunnel trajectory predictions[2] fail to compare with flight-test results. Failure of the time accurate CFD predictions is in part

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due to the assumption of inviscid flow and the resulting inability to accurately model the store passage through the shear layer. Wind tunnel testing produced both captive store (CTS) trajectory data and grid data for the weapon in proximity to the aircraft. Neither the CTS trajectories nor those produced from grid data are time accurate, which likely contributes to the inaccuracy. In addition during the flight test the launcher is believed to have flexed near the forward pusher, imparting a nose up pitching moment to the store as it was released.

With these discrepancies in mind, wind tunnel and CFD results are assessed using the uncertainty analysis tool. Further CFD runs based on the predicted weaknesses and sensitivities in the existing data set will be performed to support the analysis. Using this approach, it is anticipated that the source of the disparity between prediction and photogrammetric analysis of the trajectory can be isolated and taken into account in the trajectory models.

2.0 SIMULATION DATA

Coupled time accurate computational fluid dynamics and trajectory simulations for this paper are preformed using the Beggar code provided by the Air Force SEEK EAGLE Office (AFSEO). All simulations are performed using second order spatial discretization and first order time integration of the Euler equations on a system of overset computational grids. The trajectory is computed in the Beggar six degree-of-freedom code using fourth order Runge-Kutta time integration.

The grids for the F-111, the Small Smart Bomb (SSB), the Smart Multiple Ejector Rack (SMER), and the instrumentation pod are also provided by AFSEO. Details of the grid system and a description of the Beggar Code are provided in the paper by Coleman[1]. The conventional F-111 bay is shortened to approximately 150 inches in length (full scale) during testing due to the insertion of a bulkhead just aft of the triangular door cutouts shown in Figure 1 (right photo). Also in Figure 1 the left photo indicates the forward carriage location of the SSB. The CFD results are transformed in post processing to account for the reversed bay load out.

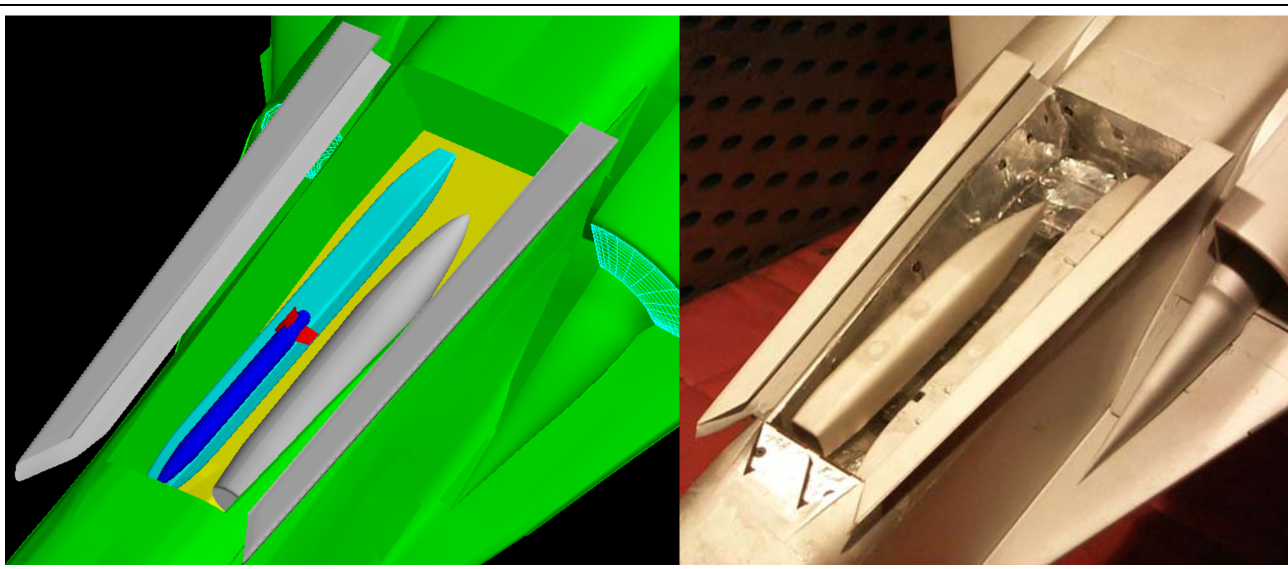

Figure 1. CFD and wind tunnel model of the F-111 weapons bay.

2.1 Time Accurate CFD Trajectory Simulations

Trajectories for the forward store release at Mach numbers of 0.8 and 0.95 (aircraft angle of attack of 3.5 degrees) are shown in Figures 3 and 4. The graphs contain the Beggar results (CFD), the wind tunnel (WT) captive trajectory system results, and the flight test trajectories (FT). All data is relative to the aircraft axis system with the origin located at the store center of gravity while in carriage (X-positive upstream, Y-positive out the right wing (pilots view), and Z-positive down). The spatial coordinates are zero at carriage while the initial orientation of the store is seen in yaw, pitch, and roll.

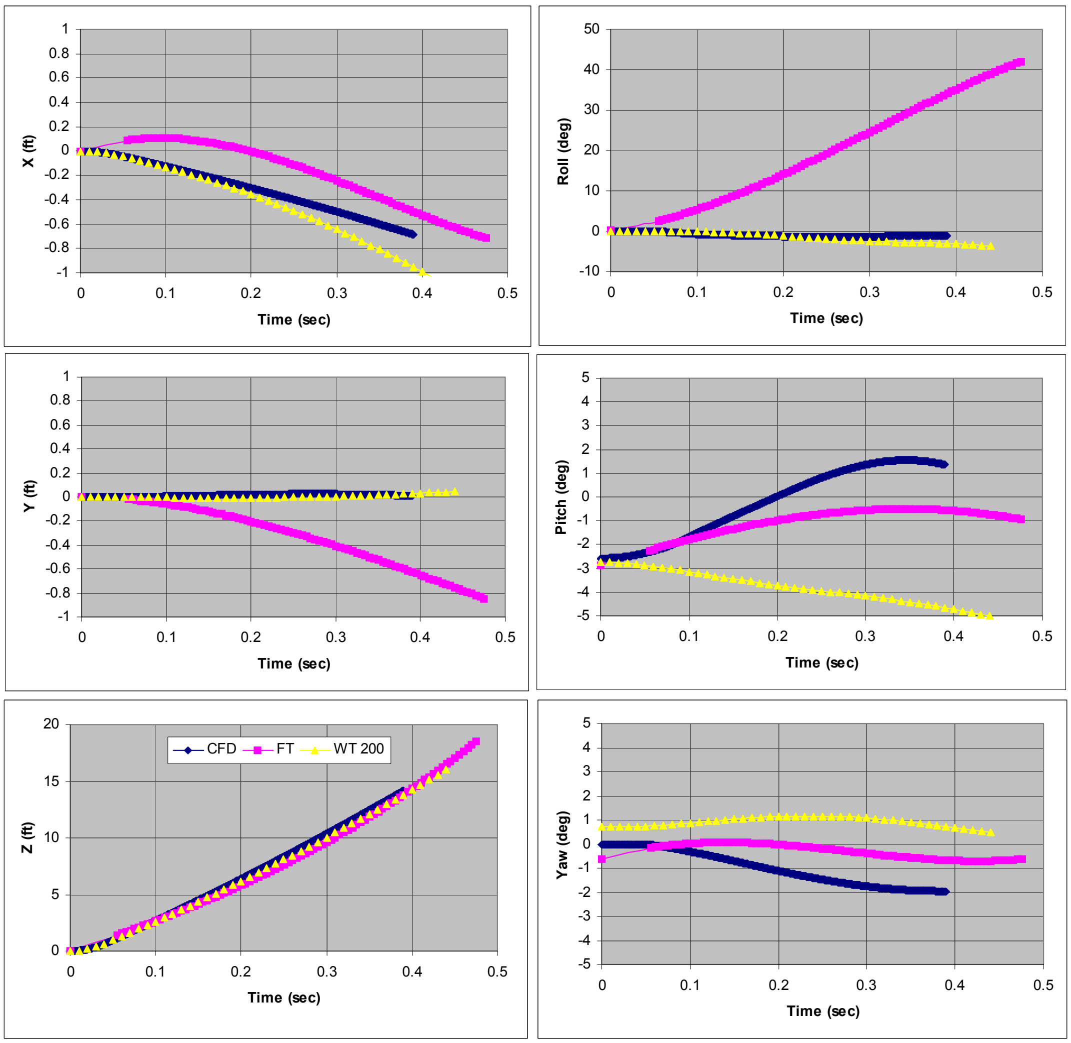

Figure 2. SSB Trajectory comparison for Mach 0.8 forward release.

The x-position of the store from both the CFD and WT compare well with flight test. Considering the store has progressed approximately 15 feet from the aircraft a difference of less than 0.4 foot is not considered significant. It should be noted that during the WT testing only a 5-component balance was available for the SSB and a value of 0.4 was assumed for the axial force coefficient. In the CFD solution inviscid flow is

assumed and it is expected that a larger normal force would be seen for a viscous solution. In the carriage position both FT and WT had the SSB at 0.74 degrees yaw (inboard/outboard respectively) while the CFD had zero yaw angle. This would also act to slightly reduce the store drag in the CFD model.

Comparison in the y-position also indicates differences between flight test and prediction of approximately 0.6-0.8 ft. Neither the CFD nor WT indicate the inboard motion of the store. During the wind tunnel CTS testing the motion of the store was restricted to pitch and translate in the ejector plane, which would inhibit motion in the y-direction. In the CFD model the motion was restricted to the z-plane during the application of ejector forces (first 0.0425 seconds). The carriage yaw of the SSB in the FT is directed inboard (0.734 degrees) while the CFD is at zero and the WT is at 0.74 degrees nose outboard. This may account for part of the differences but is not thought to be sufficient to cause the inboard motion witnessed during FT. One theory to explain the inboard motion of the SSB is that the SMER motion during the ejection imparted a lateral motion on the store (this will be discussed further).

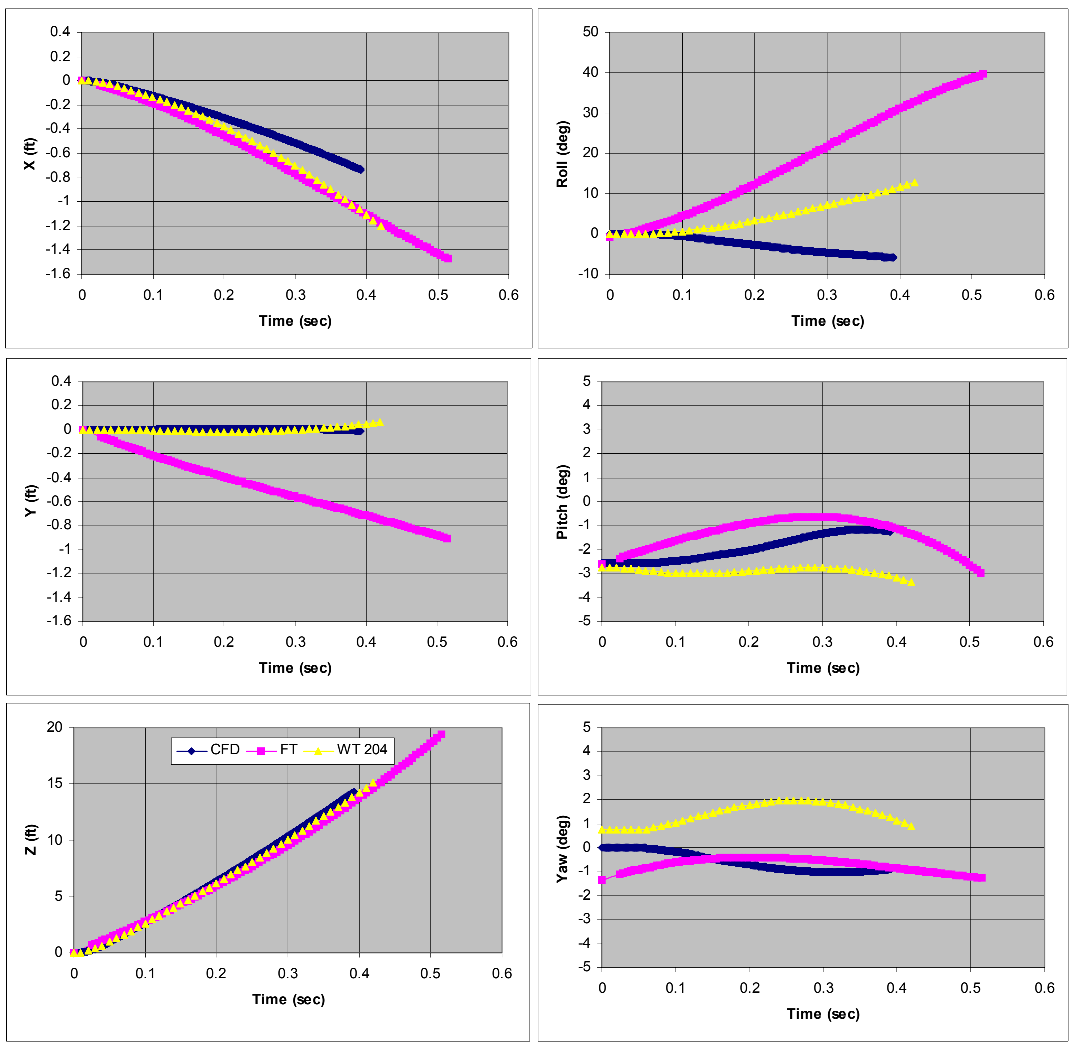

Figure 3. SSB Trajectory comparison for Mach 0.95 forward release.

All three data sources compare favorably for z location. This is expected since large ejector forces dominate the aerodynamic loads on the store.

The roll is off considerably for both flight conditions. The store moment of inertia (Ixx) was not measured for the flight test article and a value of 0.29 slug-ft^2 is assumed for wind tunnel and CFD work. There is also speculation that the SMER imparted a rolling moment to the SSB when the ejectors fired. This would seem reasonable since the ejector forces are large and the store is on the inboard carriage location of the SMER.

The pitch from the CFD simulations is comparable with the FT, while the WT data does not indicate the same trend. For the Mach 0.8 flight condition the CFD over predicts the nose up tendency of the store, however the pitch is seen to reach a maximum and the tendency is in the correct direction.

The yaw is seen to compare more favorably. For the Mach 0.8 flight condition the CFD over predicts the nose inboard tendency of the store. This plot is a little misleading due to the initial orientation of the store.

2.2 Time Averaged CFD Loads Modeling

In addition to the time accurate simulations the store is positioned at several locations beneath the aircraft to collect time-averaged loads for inclusion in the trajectory analysis code. These loads are computed by averaging time accurate the force and moment data after transients from start-up have dissipated. Store locations are chosen to correspond to selected wind tunnel grid locations and at additional locations that will bound the flight test trajectory. A table of locations and a sample comparison to wind tunnel loads will be included in the final paper.

2.3 Discussion of Test Parameters

In order to generate estimates of the uncertainty in any data set, it is necessary to examine the specifics of each test (WT, FT, or CFD) and to identify differences in set-up and accuracy of the data collection procedures. Table 1 provides a summary of many of the specifics for each of the test (blanks indicate "unknown" information at this time). The most notable differences are a max deviation (relative to nominal) in the aircraft angle-of-attack of 0.7 degrees. Wing sweep angles of 45 and 60 degrees were investigated in the WT and indicated only a small effect on the store roll (max difference of 6 degrees). While on the subject of roll it should be noted that both WT and CFD assume a value for the x-moment of inertia since no measurement was made of the actual test article. Small differences in the initial carriage orientation of the SSB are present but do not appear to significantly affect the trajectory.

The ejection system has been speculated to be a possible source of discrepancies between the three data sets. This is based on observations made of the SMER during static testing which show both an upward flexing and a rolling motion. This seems like a reasonable hypothesis since the ejection forces required to accelerate a 250 lb mass from rest to 32 fps over a distance of 8.3 inches is quite large. The discussion indicates that this scenario would provide an explanation for the FT inboard y-motion, roll, and pitch. It should be noted that no dynamic analysis of the SMER or its linkage to the aircraft has been completed. When the data for the full flight test program is reviewed the discrepancy in the pitch angle is not consistent across the Mach range and tends to discount the arguments for modifying the store pitch based on bending of the SMER. It should also be noted that the aft SSB is dropped first during FT so it is possible that the SMER has shifted prior to ejection of the forward store.

Data collection is always a challenge during testing and no more so than during a flight test. The cameras used to record the store motion do not show the store until it has travelled an estimated 8-10 inches from carriage. FT data in Figures 2 and 3 are a best fit of data collected from multiple cameras. The data is reported to have accuracies of ±2 inches in position, ±0.5 degrees in pitch, ±1 degree in yaw, and ±4 degrees in roll.

The CFD model does not include the triangular door cutouts at the bay leading edge as shown in Figure 1. During the wind tunnel test these cutouts are shown to have a significant effect on bay acoustics, but testing was not done to identify any effect on trajectory. In the CFD model the instrumentation pod geometry only approximates the actual pod. The crossectional areas are similar and should produce the same blockage effect.

	Mach 0.8 Nominal			Mach 0.95 Nominal		
Aircraft Flight Conditions	FT	CFD	WT	FT	CFD	WT
Mach	0.8	0.8	0.8	0.95	0.95	0.95
Altitude (ft)	20,000	20,000	20,000*	20,100	20,000	20,000*
Angle of Attack (degrees)	2.9	3.5	3.5	2.8	3.5	3.5
g's	0.98	1	1	0.97	1	1
Wing Sweep (degrees)	33.5	54	45	54	54	45
Store carriage						
X nose (in)		307				
Y						
Z						
Roll (degrees)	0	0	0	0	0	0
Pitch (degrees)	-2.74	-2.579	-2.74	-2.74	-2.579	-2.74
Yaw (degrees)	-0.734	0	0.73	-0.734	0	0.73
Store Properties						
length (in)	72	74	72			
Reference Area (in2)						
weigth (lb)	250.3	250	250	252.8	250	250
Xcg (in)	34.91	34.8	34.81	34.98	34.8	34.81
Ycg (in)	-0.005	0	0	-0.001	0	0
Zcg (in)	-0.003	0	0	-0.004	0	0
Ixx (slug-ft2)	NA	2.9	0.29	NA	2.9	0.29
Iyy (slug-ft2)	18.0777	18.17	18.17	18.1592	18.17	18.17
Izz (slug-ft2)	18.0868	18.17	18.17	18.1509	18.17	18.17
Ejector Properties						
force split (%)		50/50	50/50		50/50	50/50
stroke duration (sec)	0.044	0.0425			0.0425	
length of stroke (in)	8.3					
FWD pusher (in)		27.81			27.81	
aft pusher (in)		41.81			41.81	
Force magnitude (lb)		5855			5855	

Table 1. Matrix of test parameters.

3.0 UNCERTAINTY ANALYSIS METHOD

A tool called Uncertainty Management for Store Separation (UMSS) has been developed that utilizes belief function calculus to provide an assessment of the confidence associated with a force/moment prediction, determine the impact on the trajectory, and ascertain the dominant error sources. Belief function calculus is a rigorous mathematical approach that can be used to combine different pieces of related information, including uncertainty, into an overall assessment of the validity of a statement. The result is a likelihood range, referred to as an evidential interval, that describes the amount to which the data suggests that a particular outcome will occur. This approach can be construed as an extension to probability theory applied to logical statements and can be shown to mathematically reduce to the case of Bayesian probability in the absence of uncertainty.

The UMSS tool utilizes a collection of user inputs regarding a particular numerical simulation, heuristics, existing data, and physical laws to estimate the likelihood that the predicted force or moment result is within 5%, less than 10%, or greater than 10% of an unknown nominal flight reality. This likelihood is then carried using belief function calculus, through a trajectory integration to determine a trajectory envelope and its associated confidence. The underlying model for the belief function analysis has been developed in a method similarly to a QFD process in which the interdependence of different inputs are identified and the relative significance that they have on each other are estimated. At present, over 88 different input parameter intervals are specified, ranging from flight conditions to details about the test/simulations. With increased experiments, the relationships among these inputs can be improved and made more accurate. The input parameters are entered as ranges with associated confidences because most engineering numbers are not precise. For example, the flight test may be scheduled to occur at Mach 0.8, and, based on measurements, we have a high level of confidence that the actual Mach number was between 0.78 and 0.83, but only a fair confidence that the actual Mach number was between 0.7995 and 0.8002. The trajectory envelope is generated using only these ranges and the force and moment data stored in a database; thus the trajectory envelope calculation is completely independent of the confidence assessment. This decoupling separates the physical analysis from the uncertainty analysis such that changes in the underlying uncertainty model will not predict different trajectory envelopes, but only affect the confidence that one has in the accuracy of the envelope.

While the details of the model and belief function implementation in UMSS are discussed elsewhere[4], the primary input parameters examined in this study are the aircraft flight condition (Mach number, altitude, and angle of attack), the applied ejector force properties, the store mass properties, as well as parameters associated with the simulation. These parameters include grid resolution metrics, treatment of viscous terms in the CFD computations, and sting/distortion effects in the wind tunnel measurements.

4.0 TRAJECTORY COMPUTATIONS

Show impact of confidence/interval variation. Ejector, mass variations…

5.0 UNCERTAINTY SENSITIVITY ANALYSIS

The belief function calculus also provides a method to determine which input factors contributed the most to the final uncertainty, identifying inputs that should be known or controlled more precisely than others to improve the overall confidence in the results.

6.0 SUMMARY AND RECOMMENDATIONS

Conclusions from the complete analysis will be summarized here…

7.0 REFERENCES

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[4] Cary, A., Bower, W., and Wesley, L., "A Different Approach to Assessing the Uncertainty Associated with a Store Trajectory," Aircraft-Stores Compatibility Symposium XIII, 18-20 February 2003, Destin, Florida.